X · c 1 ~ 3, 1
Y ~ c 6 ~ 8

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EP 0005683A } =
WO 79/01106A }
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(54) Coupling System for Output Light of a Semiconductor Laser

(57) A coupling system for the output light (from an active layer (2) of a semiconductor laser (1) with an optical fiber 6-a or focusing lens (10). The end portion of the optical fiber (6-a) or focusing lens (10) is such that, at least in a plane parallel to the optical axis of the output light and perpendicular to the junction plane of the semiconductor laser, the width of the end portion continuously decreases towards its tip to provide a required curvature at (1/RLX, 1/RLX) the tip portion and that the distribution of light of the semiconductor laser and that of the optical fiber or the focusing lens are matched with each other in the plane perpendicular to the junction plane of the semiconductor laser. The end portion of the optical fiber or focusing lens may be formed to have a fixed width in a plane parallel to the junction plane of the semiconductor laser or so that it has a required curvature (1/RLX, 1/RLX in a plane parallel to the plane of junction of the semiconductor laser) and that the distribution of light of the semiconductor laser and that of the optical fiber or focusing lens are matched with each other also in a plane parallel to the junction plane of the semiconductor laser.

Fig. 10A

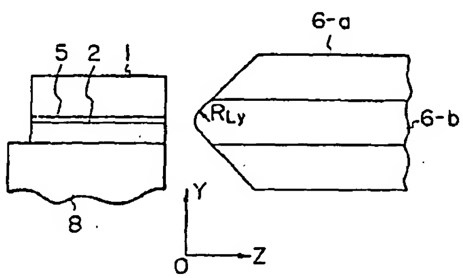

Fig. 12A

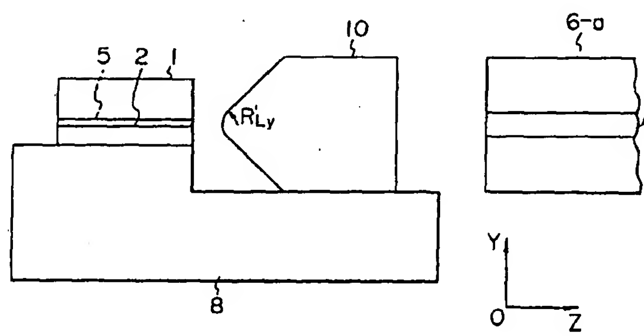

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Fig. 1A

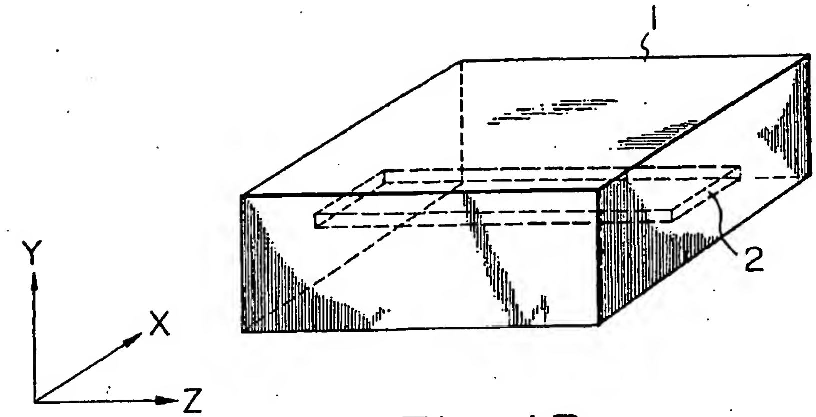


Fig. 1B

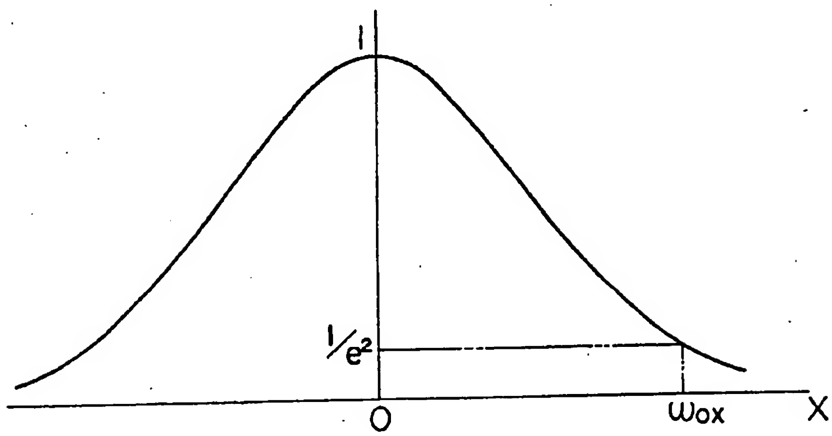


Fig. 1C

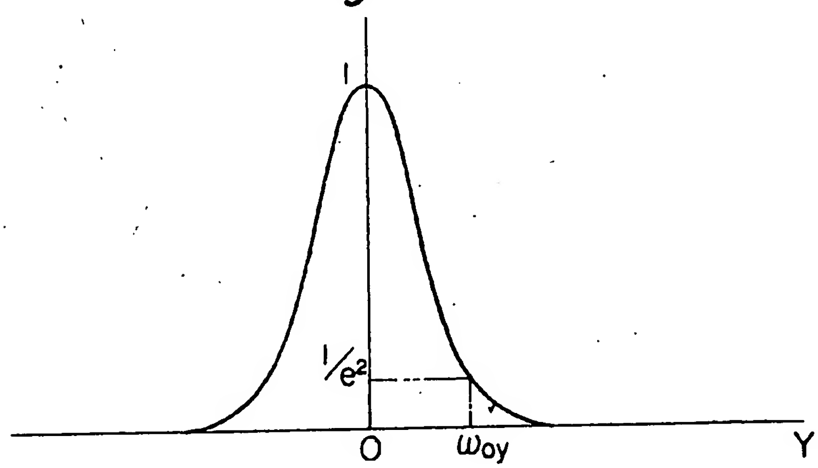


Fig. 2

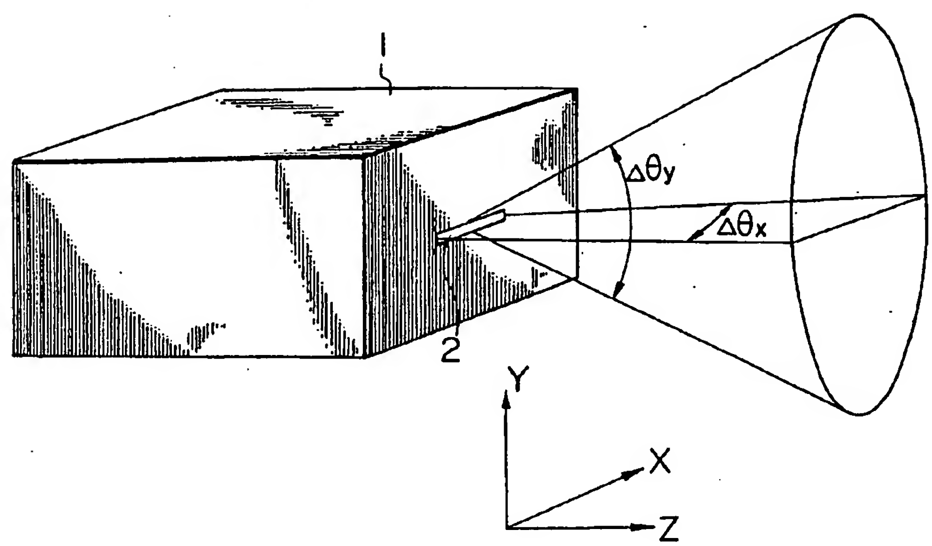


Fig. 3

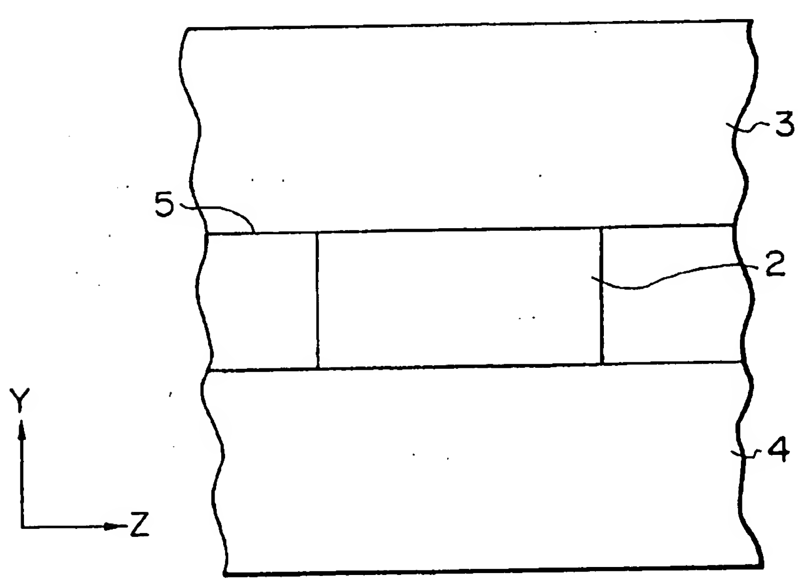


Fig. 4A

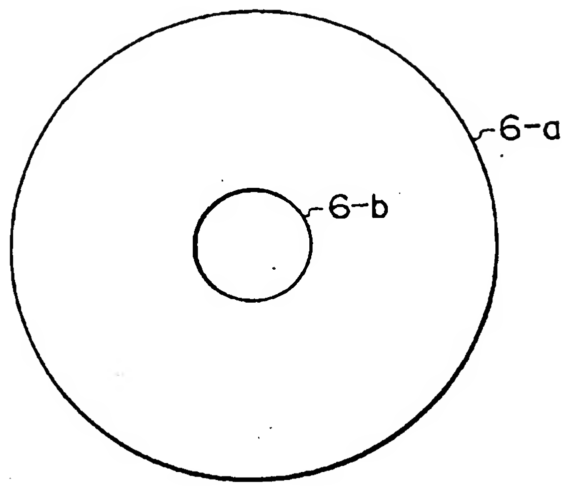


Fig. 4B

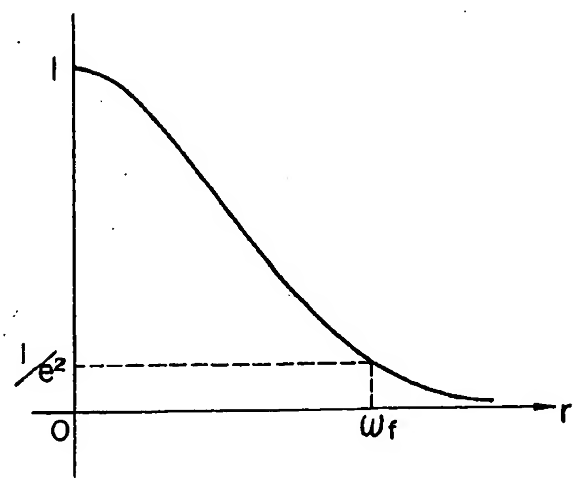


Fig. 5

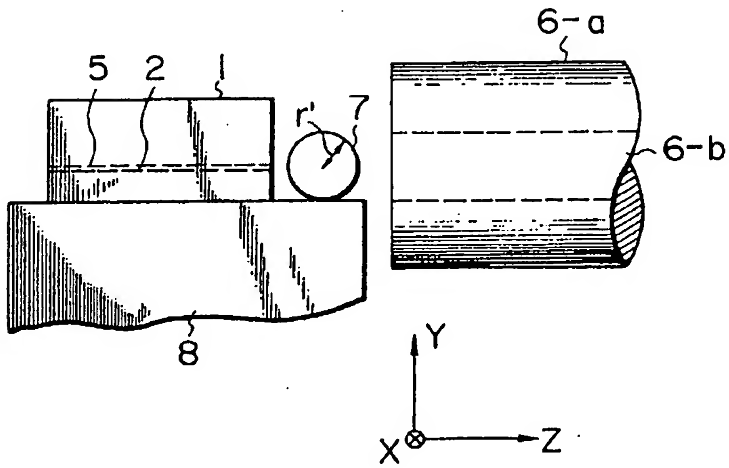


Fig. 6A

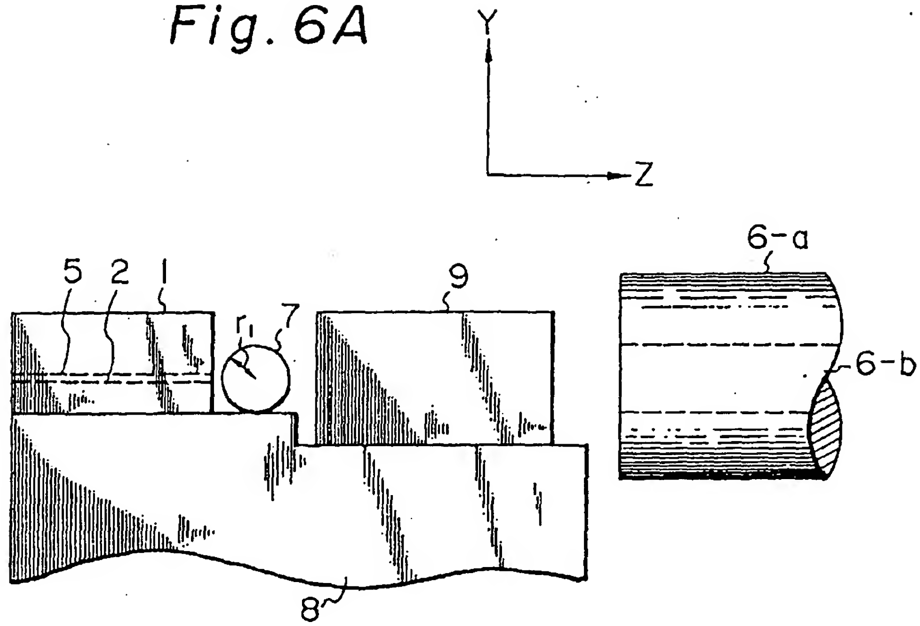


Fig. 6B

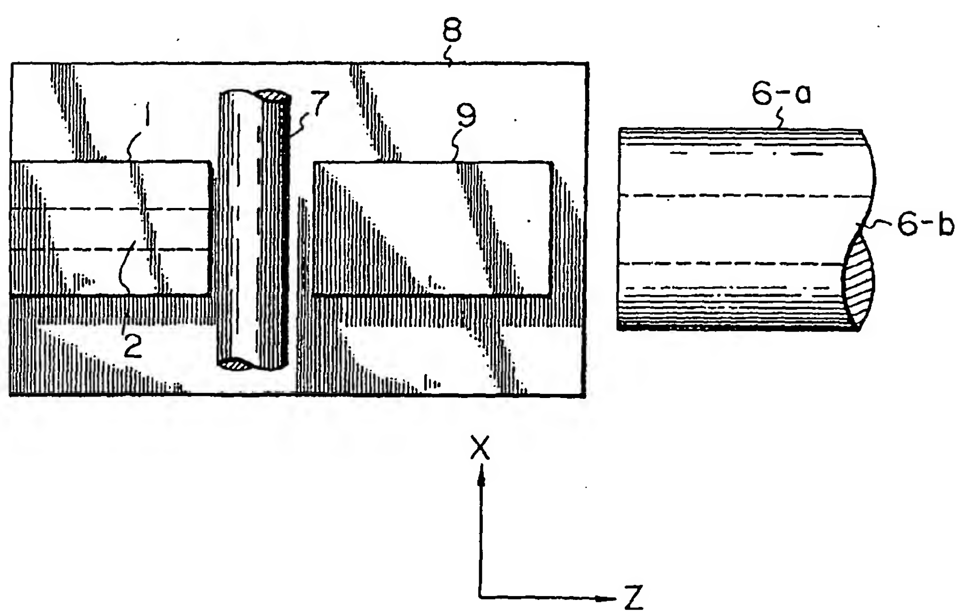


Fig.7A

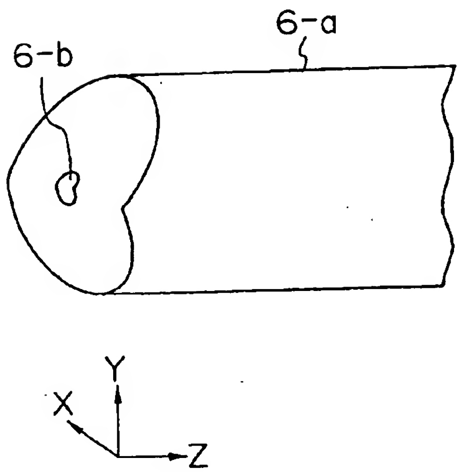


Fig.7B

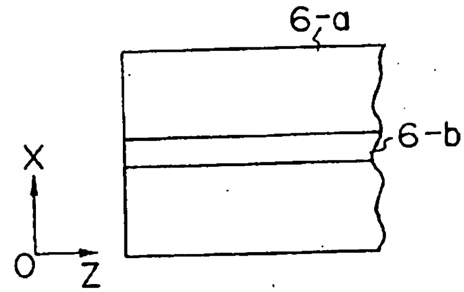


Fig.7C

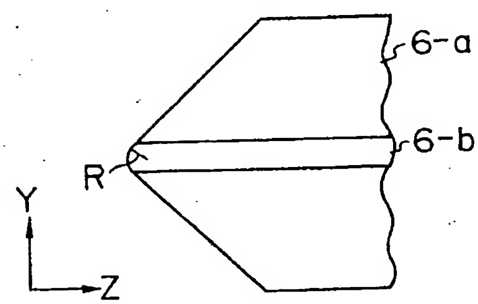


Fig.8

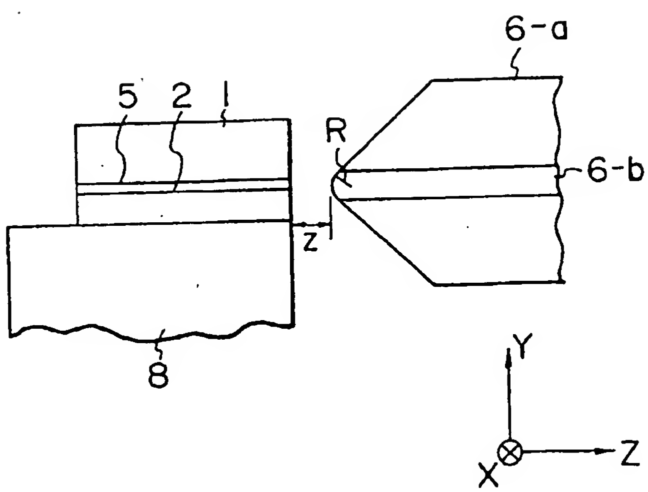
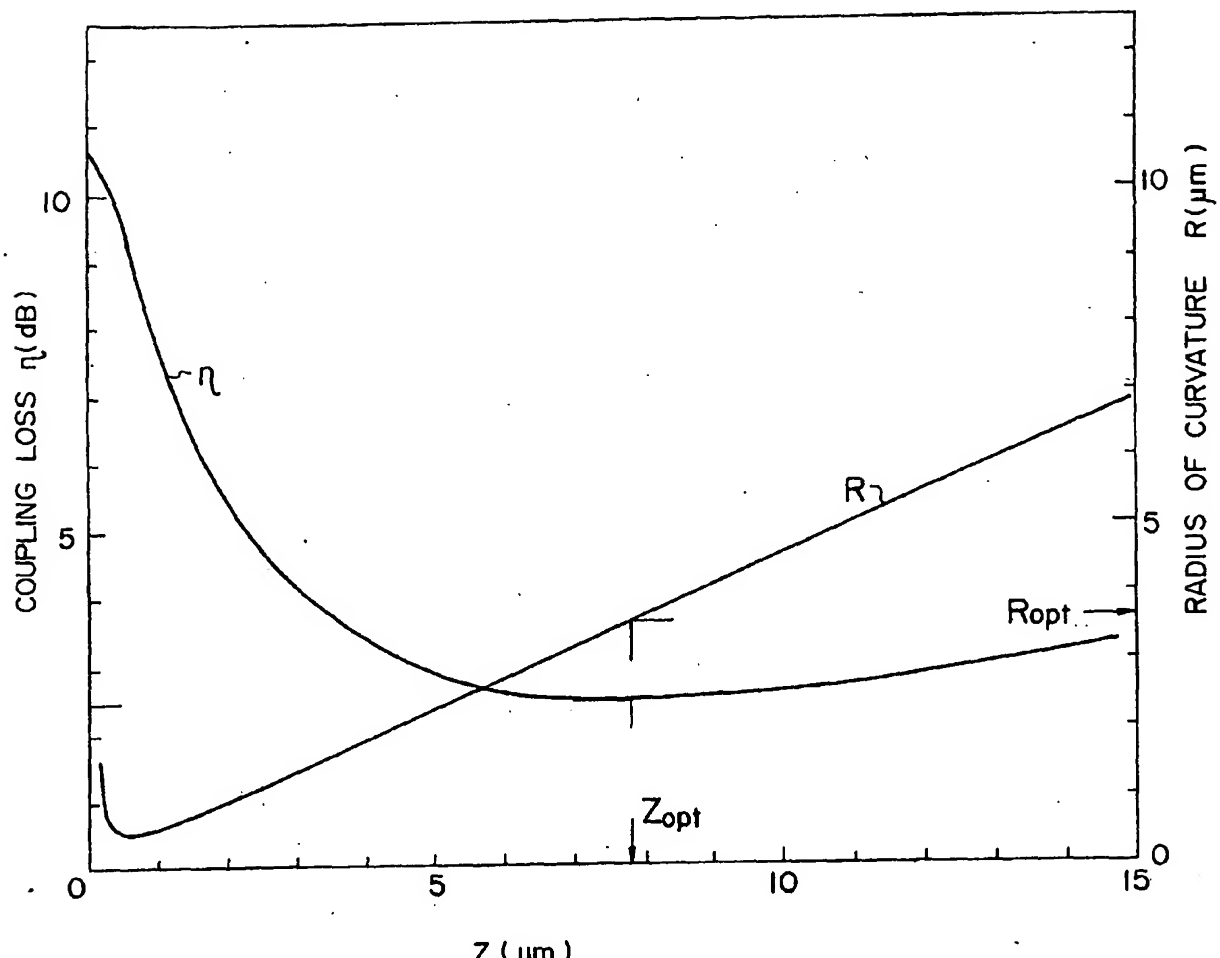


Fig. 9


COUPLING LOSS η (dB)
RADIUS OF CURVATURE R(μm)
Z (μm)
η
R
Ropt
Zopt
0
5
10
15
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5
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0
5
10

Fig. 10A

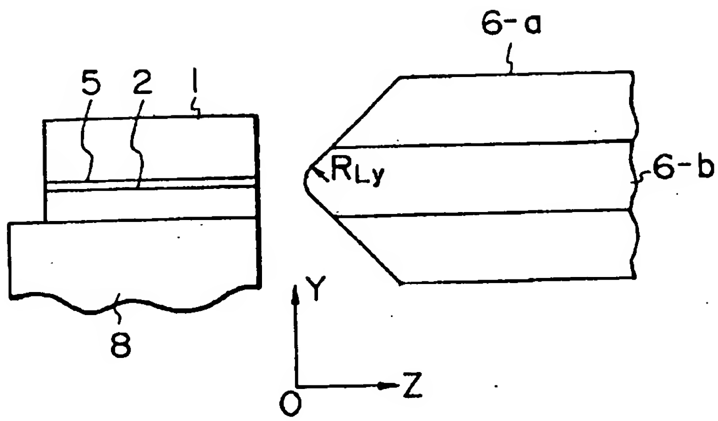


Fig. 10B

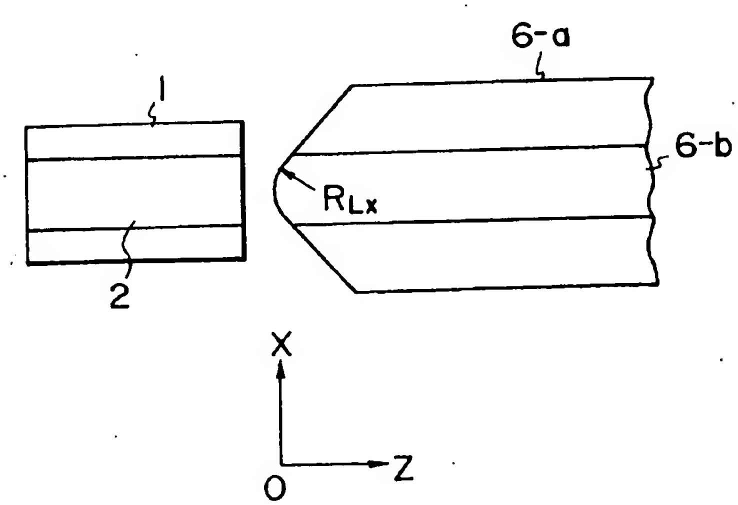
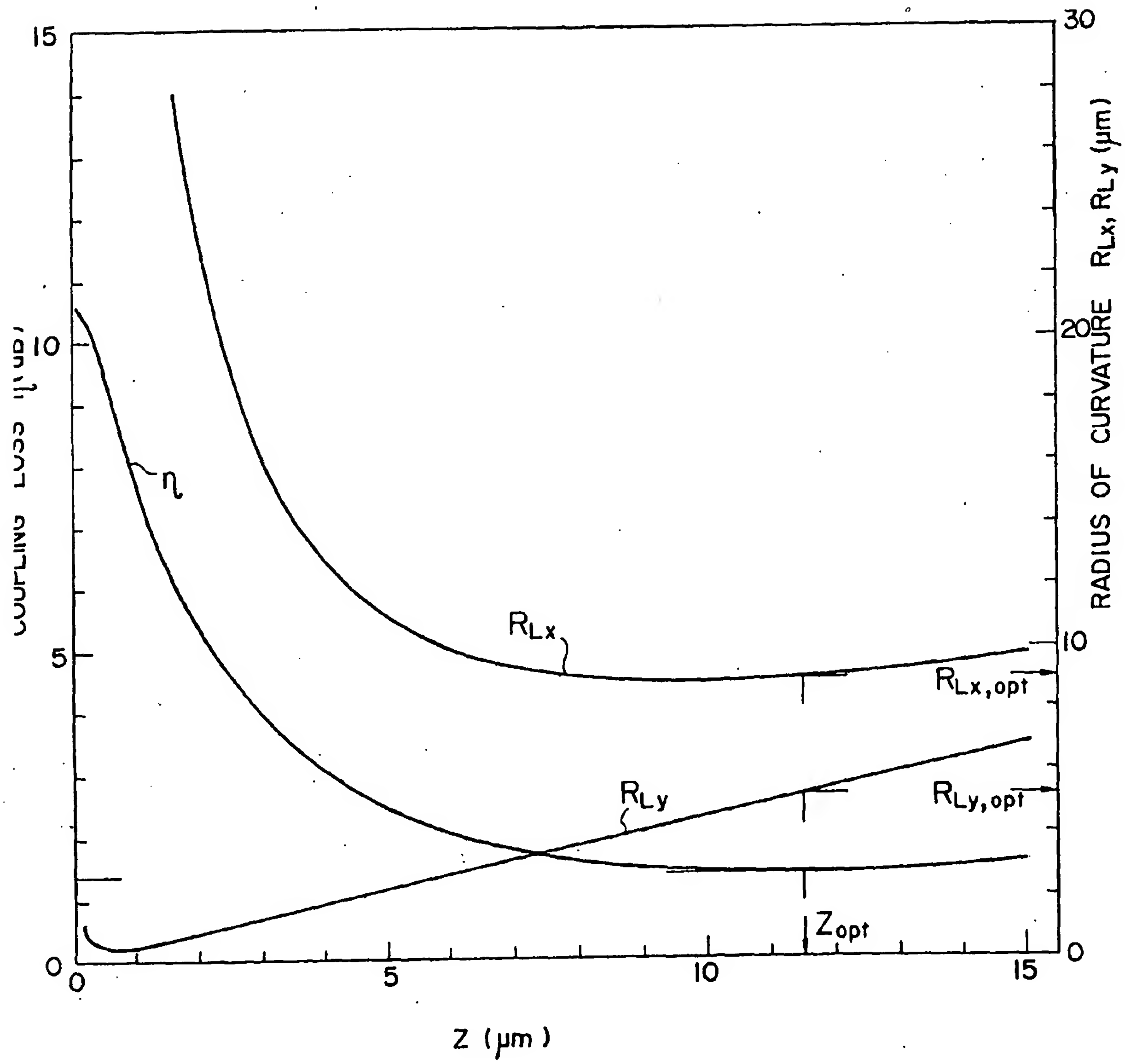


Fig. 11


15
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15
η
R_{Lx}
R_{Ly}
$R_{Lx,opt}$
$R_{Ly,opt}$
Z_{opt}
RADIUS OF CURVATURE R_{Lx}, R_{Ly} (μm)
Z (μm)

Fig. 12A

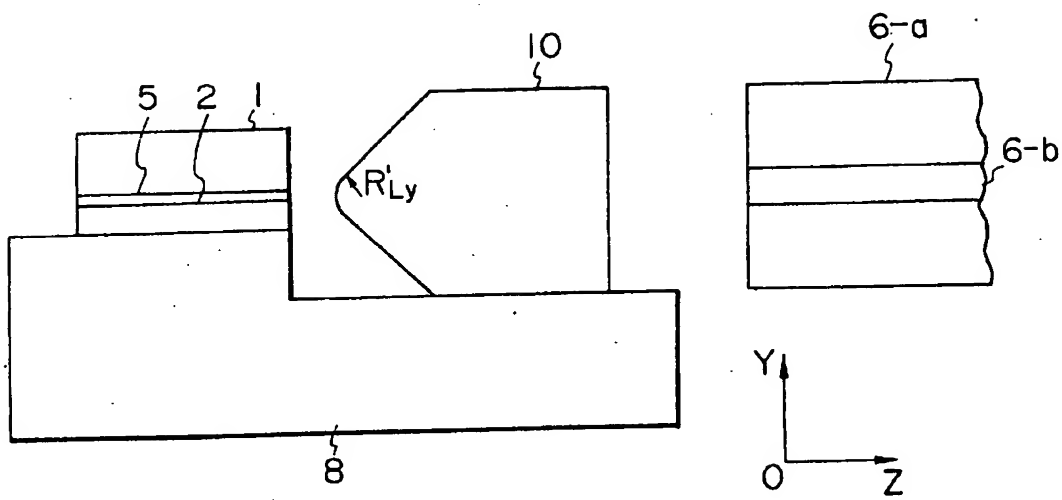
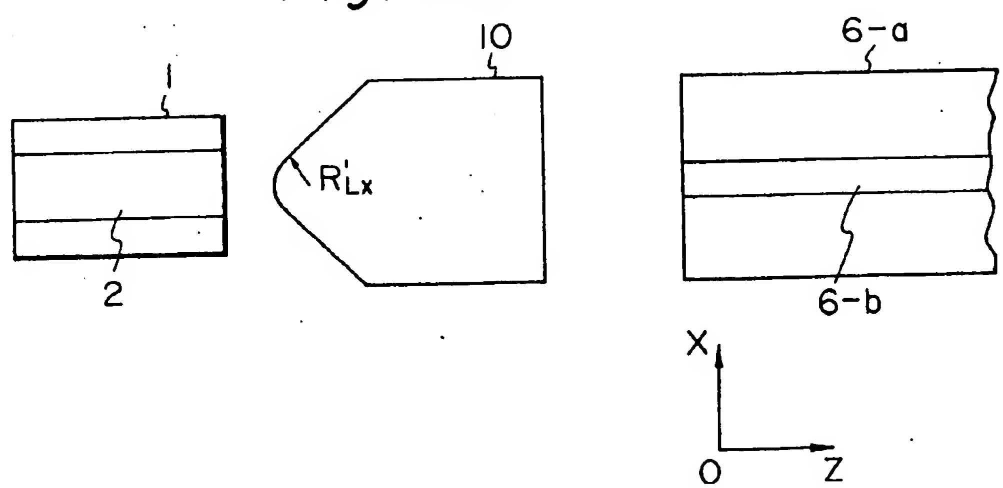


Fig. 12B



SPECIFICATION

Coupling System for Output Light of Semic nductor Laser

The present invention relates to a light coupling system, and more particularly, to a system for coupling the output light of a semiconductor laser with an optical element such as or focusing l ns.

Light coupling systems of prior art have defects, such as, for example, difficult fabrication and low mechanical strength reliability as will be described below.

An object of the present invention is to provide a coupling system which is free from the above said defects of the prior art and permits efficient coupling the output light of a semiconductor laser to an optical element such as an optical fiber.

According to the present invention, there is provided a coupling system for coupling the output light from an active layer of a semiconductor laser with an optical element, wherein an end portion of the optical element is such that, at least in a plane parallel to the optical axis of the output light and perpendicular to the junction plane of the semiconductor laser, the width of the end portion continously decreases towards its tip to provide a required curvature at the tip portion and that the distribution of light of the semi conductor laser and that of the optical element are matched with each other in the plane perpendicular to the junction plane of the semiconductor laser. The end portion of the optical element, eg an optical fiber or focusing lens, may be formed so that it has a required curvature in a plane parallel to the plane of junction of the semiconductor laser and that the distribution of light of the semiconductor laser and that of the optical element are matched with each other also in a plane parallel to the junction plane of the semiconductor laser.

Embodiments of the present invention will now be described in more detail by comparison with the prior art with reference to the accompanying drawings; in which :

Fig. 1A is a perspective view of a semiconductor laser to which the present invention is to be applied;

Figs. 1B and 1C are graphs showing normalized light intensity distributions in X- and Y-directions in an active layer of the semiconductor laser depicted in Fig. 1A;

Fig. 2 is a perspective view showing the special spread of the output light of the semiconductor laser, to which the present invention is applied;

Fig. 3 is a sectional view showing the light emitting portion and the surrounding portion of the semiconductor laser in a plane perpendicular to the optical axis;

Fig. 4A is a cross-sectional view of an optical fiber to which the present invention is to be applied;

Fig. 4B is a graph showing the normalized light intensity distribution in the cross-sectional of the optical fiber;

Fig. 5 is a side view showing an example of a conventional system for coupling a semiconductor laser with an optical fiber by means of a cylindrical lens;

Figs. 6A and 6B are a side view and a plan view showing another example of the conventional system for coupling the semiconductor laser with an optical fiber by means of a cylindrical lens and an axially symmetric lens;

Figs. 7A, 7B and 7C are respectively a perspective view of an optical fiber in an embodiment of the present invention, a longitudinal view of the fiber in the X-Z plane and a longitudinal sectional view of the fiber in the Y-Z plane;

Fig. 8 is a longitudinal sectional view illustrating another embodiment of the present invention;

Fig. 9 is a graph showing the relationships between the radius of curvature of the lens portion and coupling loss in the above embodiment;

Figs. 10A and 10B are longitudinal views of another embodiment of the present invention in the Y-Z and X-Z planes, respectively;

Fig. 11 is a graph showing the relationship between the radius of curvature of the lens portion and coupling loss in the embodiment of the present invention depicted in Figs. 10A and 10B; and

Figs. 12A and 12B are longitudinal sectional views of another embodiment of the present invention in the Y-Z and X-Z planes, respectively.

To make the differences between the prior art and the present invention clear, examples of the prior art will be described first.

With reference to Fig. 1A showing a perspective view of a semiconductor laser to which the present invention is to be applied, the light emitting portion of a semiconductor 1 is mainly limited to the inside of an active layer 2. Figs. 1A and 1C are graphs qualitatively showing examples of normarized light intensity distributions in the light emitting portion in the X- and Y-directions, respectively. In Figs. 1B and 1C, w_{ox} and w_{oy} are each a distance over which the light intensity decreases to $1/e^2$ of the intensity at the centre of the light emitting portion; this distance is commonly referred to as a spot size. The typical values of w_{ox} and w_{oy} in a planarstripe semiconductor laser emitting in the 1 μm wave-length region are about 5 and 0.5 μm, respectiv ly.

Fig. 2 qualitatively shows how the output light of the semiconductor laser spreads in space. In this case, expansion angles $\Delta\theta_x$ and $\Delta\theta_y$ of the output light in the X-axis and the Y-axis direction are approximately given by the following equation (1);

$$\Delta\theta_{x,y}=2\lambda/\pi w_{ox,y} \text{ (radian)} \quad (1)$$

where λ is wavelength and π is the circle ratio. In ordinary semiconductor lasers, since the spot sizes w_{ox} and w_{oy} in the X and Y-directions largely differ from each other, the output light emitted from the active layer 2 of the semiconductor laser 1 spreads in an elliptical form such as shown in Fig. 2.

Fig. 3 is a sectional view showing the light emitting portion and the surrounding portion of the semiconductor laser in the X-Y plane perpendicular to the optical axis. The active layer 2 is surrounded by layers 3 and 4 of smaller refractive indices than that of the active layer 2 and a current flowing in a direction along the Y-axis is narrowed, by which the light emitting portion is restricted to the inside of the active layer 2. Between the layers 2 and 3 or between 2 and 4 is formed a pn-junction plane to define the direction of flow of the current. In Fig. 3, a junction plane 5 is shown to be formed between the layers 2 and 3.

Fig. 4A shows the section of a fiber to which the output light of the semiconductor laser is to be coupled. In Fig. 4A, reference numeral 6-a indicates a fiber and 6-b designates a core. Fig. 4B shows, in connection with a case of a single mode fiber, the normalized light intensity distribution of the propagation mode in the core of the fiber. In Fig. 4B, reference character w_f identifies the radius within which the light intensity in the propagation mode is reduced to $1/e^2$ of the light intensity at the centre of the fiber, the radius being referred to as the mode radius. The value of w_f in the case of light of the 1 μm band being propagated is usually about 5 to 6 μm.

In this case, the coupling ratio η in which the output light from the semiconductor laser is coupled to the single mode fiber is given by the following equation (2):

$$\eta=\eta_x \cdot \eta_y \quad (2)$$

$$\text{where, } \eta_x=\frac{2}{(w_{ox}/w_f)+(w_f/w_{ox})}$$

$$\eta_y=\frac{2}{(w_{oy}/w_f)+(w_f/w_{oy})}$$

In the equation (2), η_x and η_y respectively indicate the coupling efficiences between the X- and Y-direciton light components of the semiconductor laser and the mode of the fiber. In the equation (2), it is assumed that the distance between the semiconductor laser and the fiber is zero and that no positional and angular deviations exist between them and further, a reflection loss (usually 4% or so) is also neglected.

Assuming that $w_f=5$ μm, that $w_{ox}=5$ μm, and that $w_{oy}=0.5$ μm, $\eta_x=1.0$, $\eta_y=0.198$ and $\eta=0.198$ are obtained. As is evident from this result, the coupling efficiency is mainly determined by a difference between the distribution of the light component in Y-direction of the semiconductor laser and the light distribution in the propagation mode of the fiber, and the wider the difference between the two distributions the more the coupling efficiency is impaired.

To avoid such a defect, it is general practice in the prior art to employ an arrangement such as that depicted in Fig. 5, in which a cylindrical lens 7 is disposed on a substrate 8 along the x-axis in a plane parallel to the junction plane 5 of the active layer 2 of the semiconductor laser 1 so that the light component in the Y- direction from the active layer 2 of the semiconductor laser 1 may be converged by the cylindrical lens 7 for efficient incidence on the core 6-b of the fiber 6-a. Letting the radius and refractive index of the cylindrical lens 7 be represented by r′ and n, respectively, its focal distance f can be expressed by $f=nr'/2\,(n-1)$. By a suitable selection of the radius r′, it is possible to match the light component of the laser 1 in the Y-direction with the propagation mode of the fiber.

The diameter of the cylindrical lens 7 is usually as small as 10 μm or so; this poses problems in terms of manufacturing and reliability of mechanical strength, and, further, introduces great difficulties in the attachment of the lens to the substrate 8 or the end face of the fiber 6-a. In addition, since the input end face of the optical fiber 6-a is flat, a portion of the semiconductor laser light is reflected by the end face of the fiber 6-a back into the active layer 2 of the semiconductor laser 1. This provides a defect such that the operation of the semiconductor laser becomes unstable.

The coupling system shown in Fig. 5 markedly improves the coupling efficiency in the Y-direction perpendicular to the junction plane 5 of the active layer of the semiconductor laser. Further, such a coupling system as depicted in Fig. 6 has been proposed for raising the coupling efficiency in the X-direction parallel to the junction plane of the active layer of the semiconductor laser. Figs. 6A and 6B are diagrams viewed from directions perpendicular and parallel to the junction plan 5 of th semiconductor laser, respectively. In a case in which th light in an elliptical spot such as depicted in Fig. 2, is emitted from the active layer 2 of the semiconductor laser 1, the Y-direction light component perpendicular to the junction plane 5 is converged by the cylindrical lens 7 and the X-direction light component parallel to th junction plane 5 passes through the cylindrical lens 7; as a result of this, the

emitted light appears in the form of a circular light beam at the output side of the cylindrical lens 7. In Fig. 6, reference numeral 9 indicates an axially symmetric lens, having a function f matching the circular light beam from the cylindrical lens 7 with the propagation mode of the core 6-b of the optical fiber 6-a and which is formed, for example, by a biconvex lens or a lens refractive index of which has a square distribution. As a result of this, not only the Y-direction light c mponent but also the X-direction light component of the semiconductor laser can be efficiently coupled to the fiber. Also in this system, however, the problems of difficult fabrication and low reliability of the mechanical strength of the cylindrical lens 7 due to its small diameter are present as in the problem of reflection of light by the fiber 6-a back to the semiconductor laser 1, as is the case with the system described above in conjunction with Fig. 5.

Embodiments of the present invention will hereinafter be described in detail.

Figs. 7 to 7C show a light-receiving end portion of a fiber formed according to an embodiment of the present invention with a view to improving the coupling efficiency of the light component perpendicular to the junction plane of the semiconductor laser. Fig. 7A is a perspective view of the end portion of the fiber; Fig. 7B is a longitudinal sectional view in a plane parallel to the X-Z plane and passing through the central axis of the fiber; and Fig. 7C is a longitudinal sectional view in a plane parallel to the Y-Z plane and passing through the fiber central axis. As depicted in Figs. 7A to 7C, the light receiving end portion of the fiber is formed in such a manner that its thickness in the Y-Z plane continuously diminishes towards the fiber tip to provide the end portion with a required radius of curvature R and that the thickness in the X-Z plane is fixed; namely, the light-receiving end portion of the fiber 6-a is formed as if it had a hemi-cylindrical lens formed as a unitary structure therewith. Such a fiber end portion can be easily obtained by polishing one end portion of a fiber into a wedge-like shape and then subjecting it to a chemical etching or heat-fusion technique. Further, since the portion of the radius of curvature R, which corresponds to a hemi-cylindrical lens for matching use, is formed as a unitary structure with the fiber, the problem of mechanical strength arising from the small diameter of the lens is solved and no lens need be installed on the mount.

Fig. 8 illustrates an embodiment of the semiconductor laser-fiber coupling system of the present invention in the Y-Z plane passing through the fiber central axis. The Y-direction light component in the active layer 2 of the semiconductor laser 1 mounted on the substrate 8, is enlarged by the curved portion at the tip of the fiber 6 and matched with the light distribution of the propagation mode of the core 6-b, allowing a highly efficient coupling. By selecting the radius of curvature R at the tip of the fiber as given by the following equation (3), the Y-direction light component of the semiconductor laser and the light distribution of the propagation mode of the fiber can be matched with each other.

$$R=(n'-1)\,.\,R_y \tag{3}$$

where

R_y is given by the following equation (4):—

$$R_y=\{4z^2+(kw_{oy})^2\}/4z \tag{4}$$

where n′ is the refractive index of the fiber core, z is a distance between the semiconductor laser and the fiber tip and $k(=2\pi/\lambda, \lambda$ being wavelength) is the wave number.

In this case, the coupling efficiency η is given by the following equation (5):

$$\eta=\frac{4}{w_f^2 w_x w_y\sqrt{(1/w_x^2+1/w_f^2)^2+(k/2R_x)^2\,(1/w_y^2+1/w_f^2)}} \tag{5}$$

where

$$R_x=4z^2+(kw_{ox}^2)^2/4z \tag{6}$$

$$w_x=\sqrt{4z^2+(kw_{ox})^2}/(kw_{ox}) \tag{7}$$

$$w_y=\sqrt{4z^2+(kw_{oy}^2)^2}/(kw_{oy}) \tag{8}$$

where $w_{x,y}$ represent spot sizes of the X and Y components of the laser output beam at a position spaced a distance z apart from the end face of the semiconductor laser and $R_{x,y}$ represents curvatures of the phase fronts of the X and Y components of the laser output beam at the position z. In connection with a case of using a semiconductor laser having parameters such as w_{ox}=0.24 μm, w_{oy}=0.51 μm and λ=1.32 μm and a single mode fiber having a mode radius w_f=6.56 μm, Fig. 9 shows the relationships of the curvature radius R and the coupling efficiency n to th distance z between the semic nductor laser and the fiber tip which ar obtained from th quati ns (3) and (5). In Fig. 9, the coupling efficiency η is represented in t rms of coupling loss in dB. It appears from Fig. 9 that there exists Z_{opt} which minimizes th coupling loss and that an optimum value R_{opt} of the radius of curvature is determined in corresp ndence to this Z_{opt}.

In accordance with the present invention, the curved portion of optical matching is formed of the fiber itself, so that unlike the prior art xamples there is no discontinuity in refractive index between th lens and the fiber; this markedly improves the stability of the semiconductor laser operating characteristics with respect to the reflection of light back into the active layer 2 of the semiconductor laser.

Figs. 10A and 10B illustrate another embodiment of the present invention for coupling the output light of a semiconductor laser with a fiber. This embodiment is intended to increase the coupling efficiency in the direction parallel to the junction plane of the semiconductor laser as well as in the direction perpendicular thereto. Fig. 10A is a section in a plane perpendicular to the junction plane 5 of the semiconductor laser 1 and passing through the fiber central axis, and Fig. 10B is a section in a plane parallel to the junction plane 5 of the semiconductor laser 1 and passing through the fiber central axis. That is, the light-receiving end portion of the fiber 6-b is shaped to be hemi-ellipsoidal. Such a configuration can be achieved by polishing one end portion of the fiber 6-b into a quadrangular pyramidal form first and then subjecting it to heat fusion or chemical etching.

In Figs. 10A and 10B, the radius of curvature of the light-receiving end portion of the fiber is R_{Ly} in the Y-Z in the X-Z plane, which are respectively given by the following equations (9) and (10):

$$R_{Ly}=(n'-1)R_y \tag{9}$$

$$R_{Lx}=(n'-1)R_x \tag{10}$$

where n' is the refractive index of the fiber core and R_y and R_x are given by the aforementioned equations (4) and (6). The coupling efficiency η in this case is given by the following equation (11):

$$\eta=\frac{4}{(w_f/w_x+w_x/w_f)(w_f/w_y+w_y/w_f)} \tag{11}$$

where w_f is the mode radius of the fiber and w_x and w_y are respectively given by the equations (7) and (8). In Fig. 11 the relationships of the radii of curvature R_{Lx} and R_{Ly} of the light-receiving end portion of the fiber and the coupling efficiency η with respect to the distance z between the semiconductor laser and the tip of the fiber are shown using the parameters of the semiconductor laser and the single mode fiber employed in the calculation for obtaining the characteristics of Fig. 9, that is, $w_{ox}=2.04\ \mu m$, $w_{oy}=0.51\ \mu m$, $\lambda=1.32\ \mu m$ and $w_f=6.56\ \mu m$. Also in this example, the coupling efficiency is represented in terms of the coupling loss in dB. Fig. 11 indicates that there exists Z_{opt} which minimizes the coupling loss n and that the radii of curvature R_{Lx} and R_{Ly} of the light-receiving end portion of the fiber in the X-Z and the Y-Z plane are determined to correspond to the abovesaid Z_{opt}.

With this embodiment, since the hemi-ellipsoidal lens for matching is formed as a unitary structure with the fiber itself, the problem of reliability of mechanical strength arising from the small diameter of the cylindrical lens is settled and there is no need to install a cylindrical lens on a mount. Further, the axially asymmetric lens 9 used in the prior art example of Figs. 6A and 6B becomes unnecessary. Moreover, the unstableness of the operating characteristics of the semiconductor laser which is caused by the optical feedback to the semiconductor laser is improved because no discontinuity of the refractive index exists between the lens portion and the fiber. In addition, with this embodiment, the output light of the semiconductor laser having arbitrary section for the active layer can be coupled to the fiber with high efficiency.

Figs. 12A and 12B illustrate still another embodiment of the present invention and are respectively sectional views in the Y-Z plane and the X-Z plane passing through the fiber central axis and are perpendicular and parallel to the junction plane of the semiconductor laser, respectively. In Figs. 12A and 12B, reference numeral 10 indicates an axially symmetric focusing lens, which is designed so that the radii of curvature of its one end portion on the side of the semiconductor laser are R_{Ly}' and R_{Lx}' in the Y-Z and X-Z plane, respectively. Light emitted from the active layer 2 of the semiconductor laser 1 on the substrate 8 is converted by the hemi-ellipsoidal end portion of the focusing lens 10 into parallel beam in both of the X and Y directions and focused by the lens on the core 6-b of the fiber 6-a. In this case, the radii of curvature R_{Ly}' and R_{Lx}' of the light-receiving portion of the focusing lens 10 in the Y-Z and the X-Z plane can be obtained by the same method as used for obtaining the radii of curvature of the light-receiving end portion of the fiber in Fig. 11. Namely, it is sufficient to design so that, immediately after passing through the hemi-ellipsoidal light receiving end portion of the focusing lens 10, an elliptical light beam from the active layer 2 of the semiconductor laser 1 is converted into parallel beams having spot sizes w_x and w_y in the X- and Y-directions, respectively, then subjected to the axially symmetric lens action by th focusing lens 10 and converted again into parallel beams of the spot sizes w_x and w_y on the light-receiving end face of the fib r 6-a for incidence on the core 6-b thereof. The focusing lens 10 can be obtained by polishing into a quadrangular pyramidral form one end portion of a fiber or lens not shown formed to an axially symmetric convex on another side or one end portion of a lens the refractive index of which has a

square distribution, and then by subjecting the polish d nd portion to h at fusion or chemical tching.

In accordance with the present invention, the hemiellipsoidal lens for matching use is formed as a unitary structure with the following lens, by which is s ttled the problem f reliability of mechanical strength resulting from the small diameter of the cylindrical lens, encountered in the prior art example of Fig. 6, and no cylindrical lens is required. Further, since the substrate having the semiconductor laser 1 and the focusing lens 10 and the fiber 6-a can be spaced apart, the degree of freedom mounted thereon with regard to packaging the semiconductor laser is increased.

Although the foregoing description has been given in connection with the case of coupling the semiconductor laser to a single mode fiber, the same effect as described in the foregoing can also be produced in the coupling of a multi-mode fiber to the semiconductor laser. Further, the same effect as described above can be obtained coupling a fiber to a thin film waveguide except that the direction of propagation of light is reversed.

As has been described above in detail, the present invention achieves a highly reliable coupling system which allows ease in coupling a semiconductor laser to an optical fiber and in addition, the invention permits high-efficiency coupling which avoids the unstable operation of the semiconductor laser which comes from optical feedback; accordingly, the present invention is of great utility from an industrial view point.

Claims

1. A coupling system for coupling the output light from an active layer of a semiconductor laser with an optical element, wherein an end portion of the optical element is such that, at least in a plane parallel to the optical axis of the output light and perpendicular to the junction plane of the semiconductor laser, the width of the end portion continuously decreases towards its tip to provide a required curvature at the tip portion and that the distribution of light of the semi conductor laser and that of the optical element are matched with each other in the plane perpendicular to the junction plane of the semiconductor laser.

2. A system according to claim 1, wherein the end portion of the optical element has a fixed width in plane parallel to the junction plane of the semiconductor laser.

3. A system according to claim 1, wherein the end portion of the optical element has a required curvature in a plane parallel to the plane of junction of the semiconductor laser and that the distribution of the light of the semiconductor laser and that of the optical element are matched with each other also in a plane parallel to the junction plane of the semiconductor laser.

4. A system according to any one of claims 1 to 3 wherein the optical element is an optical fiber.

5. A system according to any one of claims 1 to 3 wherein the optical element is a focusing lens.

6. A coupling system for the output light of a semiconductor laser substantially as herein described with reference to any of Figures 7A to 11 or Figures 12A and 12B of the accompanying drawings.

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